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February 20, 1963

R-2-63-4

STUDY OF TECHNIQUES FOR A HIGH POWER, FAST WAVE PLASMA CYCLOTRON AMPLIFIER

Third Quarterly
Interim Engineering Report
Contract No. AF33 (657)-8852
Task No. 404006

Prepared by

Edwin Langberg
Maiken Naylor
David Park

Submitted to

Aeronautical Systems Division
Attn: ASRNET-1 - Contract AF33(657)-8852 Item II
Wright-Patterson Air Force Base, Ohio

ELCON LABORATORY, INC.
Subsidiary of Metcom, Inc.
60 Arsenal Street
Watertown, Massachusetts

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1. Fast Wave Cyclotron Amplification

In view of the evolution of the basic fast wave cyclotron amplification concept, it may be appropriate in this introductory section to discuss in general terms the present status of the basic understanding of the process. By definition fast wave amplification is based on a negative conductivity component of the plasma which causes the growth of an electromagnetic wave passing through it. The dielectric constant of the plasma need not differ significantly from that of free space since the plasma is not used to slow down the propagating wave. In general, the plasma frequency is well below the signal frequency to be amplified for all applications described here.

The basic advantage of the fast mode of plasma amplification as compared with a slow wave plasma amplification is the ease of coupling to and from the plasma and the potential broad-band properties which are associated with this mode of amplification. Further, one is not restricted at high microwave frequencies by electron densities which can be realized practically and which provide the upper frequency limit for use of plasma as a slow wave medium.

The original concept[1] of fast wave plasma cyclotron amplification is based on the presence of the cyclotron field alone in the interaction region. The electrons may be introduced

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[1] G. Bekefi, L. Hirshfield, and S. C. Brown, "Kirchoff's Radiation Law for Plasma with Non-Maxwellian Distribution," Physics of Fluids 4, 173 (1961).

into this region by some external means: e.g., by injection of an essentially mono-energetic beam emerging from a sheath surrounding a thermionic emitter. The plasma is only weakly ionized and contains a gas with a rapidly varying collision cross section as a function of electron energy. For certain weakly ionized gases such as mercury, cesium, argon, and xenon, the slope of the collision cross section with energy is positive and sufficiently high to assure a basic condition for amplification, namely that

$$Q \frac{\partial}{\partial u} \left(\frac{u}{Q} \right) < 1 \qquad \ldots(1.1)$$

where u is the electron energy and Q is the collision cross section.

The bandwidth in which amplification takes place is given by

$$|\omega - \omega_b| < \nu \qquad \ldots(1.2)$$

where ω_b is the cyclotron frequency.

The electron injected in such plasma can give up the energy difference between its original injection energy u_o and the minimum energy u_m below which Eq. (1.1) is no longer satisfied. The essential aspect of an efficient design of an amplifier of this type is therefore centered on the problem of removal of electrons once they reach the energy u_m without removing electrons of higher energy. If the electrons below energy u_m

are left in the plasma, they will cause attenuation. If on the other hand the electrons above energy u_m are removed then the efficiency of their utilization is reduced. Further, a basic and inherent limitation on efficiency is that ideally only the energy differential $(u_o - u_m)$ can be removed per electron and that the emission of this electron involved an expenditure of the energy equal at least to the work function of the cathode.

It appears therefore that even though a single field cyclotron amplifier may be possible it is difficult to envisage an efficient solution to some of its fundamental problems.

Our attention therefore was directed to a different method of cyclotron amplification in which two field components are present simultaneously: i.e., the cyclotron field and the "pumping" field which conveniently could be a d.c. field. In order to clarify the difference in operation between a single field component and a two component amplifier, let us consider first the situation where the electron beam is again injected with original velocity corresponding to the condition where Eq. (1.1) is satisfied, but in addition to the cyclotron field there is also a d.c. field directed along the magnetic field. The time between collisions depends on the energy gain or loss of an individual electron. Specifically, an electron which is in the correct phase to lose its energy to the cyclotron field will tend to stay longer between collisions and consequently in addition to giving up more energy to the cyclotron field will also have a chance to pick up more energy from the d.c. field.

There are two potential advantages of this technique as compared with the single field component technique:

a) There is no need to replenish each electron after the energy differential $u_o - u_m$ has been given up to the cyclotron field, and consequently one obtains more energy transfer per electron and less expenditure of energy on electron generation.

b) There is no need for highly selective removal of electrons from the plasma.

Specific experimental attention has been given in this reporting period to the configuration where the d.c. field is parallel to the B field. However, one should not preclude the possibility of the application of a d.c. pumping field perpendicular to the B field even though the interaction in this case differs from that described above.

When the pumping d.c. field is in the z direction parallel to the B field, the pumping d.c. field can be obtained by means of variation of space charge in the tube. Controlled variation of space charge and resultant E_z field can be obtained by controlling ion losses due to ambipolar diffusion to the walls. This control mechanism will be described in some detail in Section 2. D. C. pumping field perpendicular to the magnetic field can be maintained in the plasma by virtue of tensor plasma conductivity. This method provides additional freedom in control of the d.c. pumping electric field and the resultant electron energy and may be considered further in the future.

One specific problem which is encountered in the design of an amplifier with $E_{dc} \parallel B$ is that one must satisfy the condition that the conductivity for the d.c. field is positive (and therefore results in "pumping" of the electron gas) while the cyclotron conductivity is negative which is required by the conditions of gain. The previous quarterly report discusses in some detail the conditions under which both of these criteria can be satisfied.

The experimental program reported for this quarter is based on gas mixtures described in the previous quarterly report and is directed toward the exploration of cyclotron gain mechanism in a gas mixture exhibiting negative differential conductivity under conditions of the d.c. pumping field in the direction of the B field and the cyclotron field perpenducular to it.

2. Gas Mixture in an Axial Electric Field

The second quarterly report considers in detail the properties of certain gas mixtures which exhibit a negative slope of current-voltage characteristics. Qualitatively a plasma biased to the point where dv/dE is negative represents a medium where the rate of extraction of electron energy by the r.f. field is exceeded by the reduction of plasma losses in electron collisions. This represents an unstable solution in which the r.f. power will increase until a new equilibrium situation is reached in which the generated r.f. power is just equal to the reduced plasma loss.

The experimental curves[2] giving the drift velocity as a function of E/p are given in Figure 1 for argon - CO_2 mixtures and in Figure 2 for xenon - CO_2 mixture. From the point of view of the design of an experiment it is important to interpret the region of negative slope in terms of electron energy. In average electron theory the drift velocity is

$$v = \frac{e}{m} Et = \frac{e}{m} E/cpP \qquad \ldots(2.1)$$

where e is the electron charge, m the electron mass, c the electron speed (proportional to the square root of electron energy), p is the pressure in Torrs and P is the "probability"

[2] W. H. English and G. C. Hanna, "Grid Ionization Chamber Measurements of Electron Drift Velocities in Gas Mixtures," Canadian J. of Phys. 31, 768 (1953).

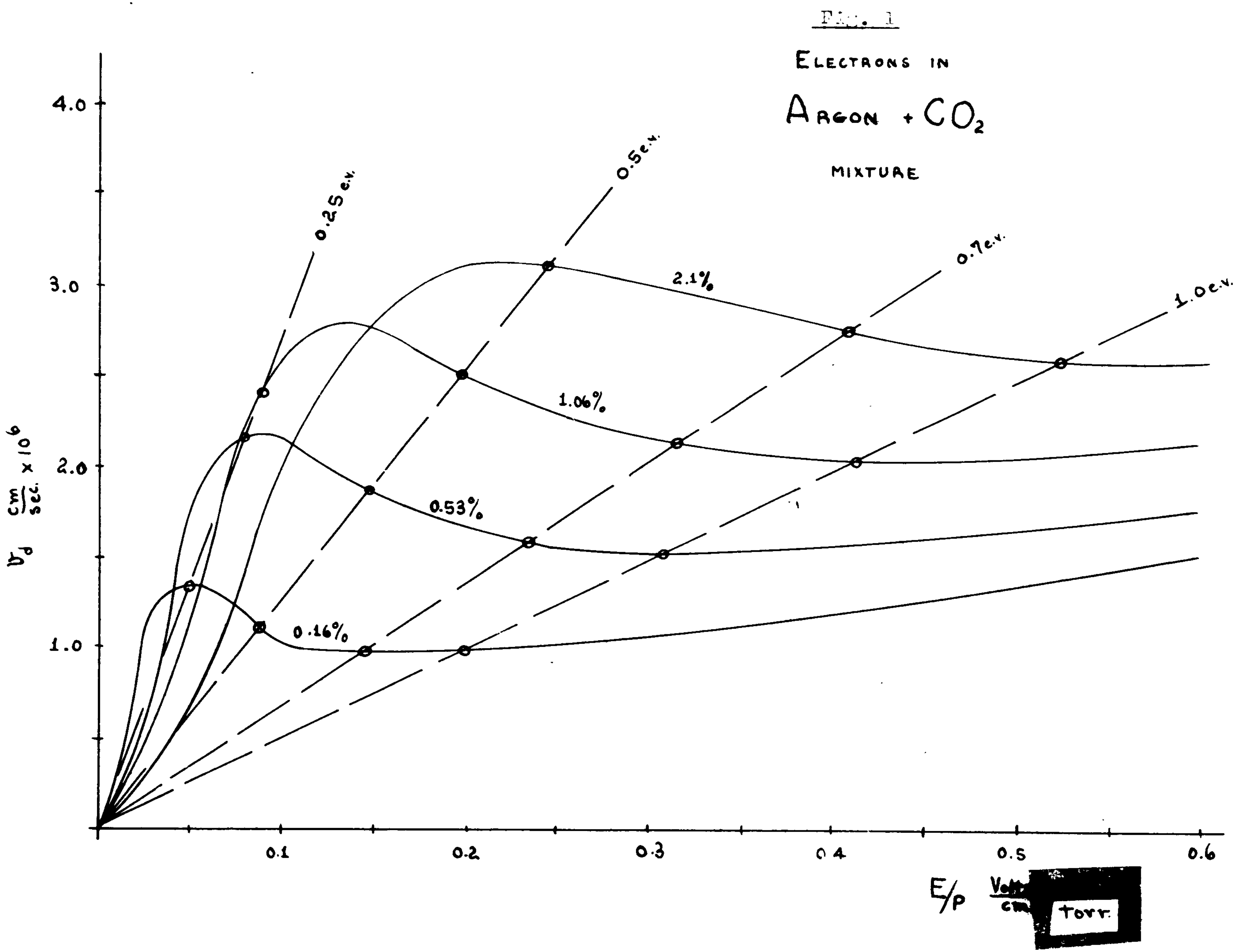

Fig. 1

ELECTRONS IN

ARGON + CO_2

MIXTURE

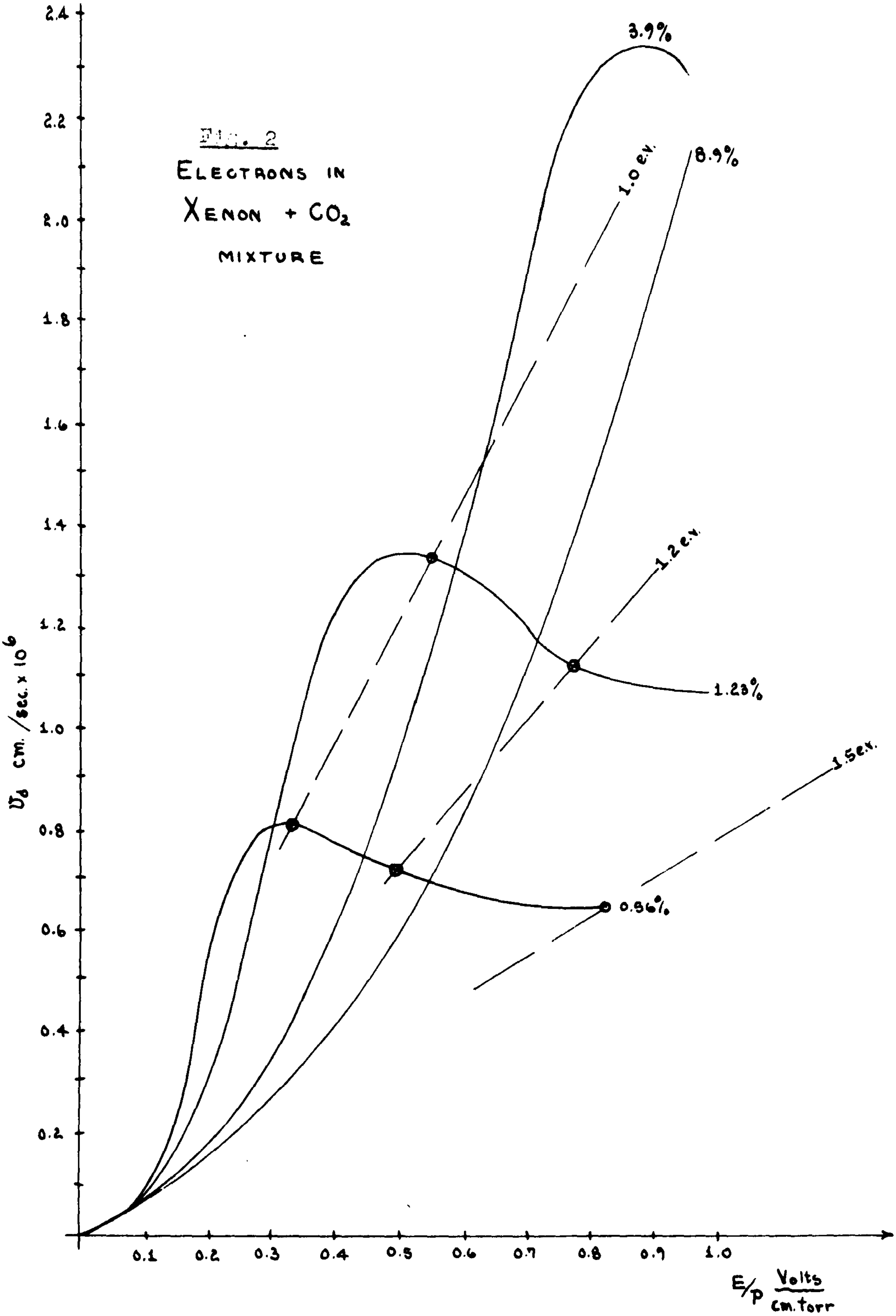

Fig. 2
Electrons in Xenon + CO_2 mixture

of collision, which is in general also a function of energy. It follows that

$$\frac{E}{p}\,\frac{1}{v} = \frac{m}{e}\,cP \qquad \ldots(2.2)$$

The right hand side is a function of electron energy only and consequently the line of constant slope from the origin of the E/p vs v plot corresponds to a specific electron energy. If u is in electron volts, E/p in volts/cm Torr, and v in cm/sec x 10^6 then

$$P\sqrt{u} = 24\,\frac{E}{p}\,\frac{1}{v} \qquad \ldots(2.3)$$

Based on the above equation the average electron energy corresponding to various regions of the negative slope was calculated and is shown in Figure 1 and Figure 2. As could be expected, the negative slope corresponds to an identical energy range for a given gas combination. The reason that the negative slope region varies as a function of E/p for different percentages of the impurity gas is caused by the increase of electron losses due to carbon dioxide.

The formulation of the conditions for negative slope of the E/p vs v curve in terms of electron energy is very convenient for calculation of plasma conditions when ambipolar diffusion of ions to the walls determines the potential distribution.

A lossless plasma has the tendency to present an equipotential region to slow variations in the electric field. The reason for it is that any instantaneous disturbance in d.c. potential is equalized by a flow of charge. However, plasma can sustain d.c. potential gradients and corresponding gradients in space charge to offset the losses caused by diffusion of charged particles to the walls.

The problem of a plasma (positive column) without a magnetic field in a long cylindrical tube has been treated[3] in the literature. The basic requirement for an equilibrium plasma is that the number of ionizing collisions in a plasma volume must be exactly equal to the losses. The losses of charged particles at the plasma boundary are governed by well known ambipolar diffusion theory. The number of ionizing collisions depends on the average electron energy and the energy distribution. Based on the assumption of reasonable electron distribution, Reference 3 relates in the graphical form the ratio of average electron energy to ionization energy as a function of gas properties, gas pressure, and the diffusion length. This graph in somewhat modified form is represented in Figure 3.

For a cylindrical tube of length L and radius R the diffusion coefficient is given by

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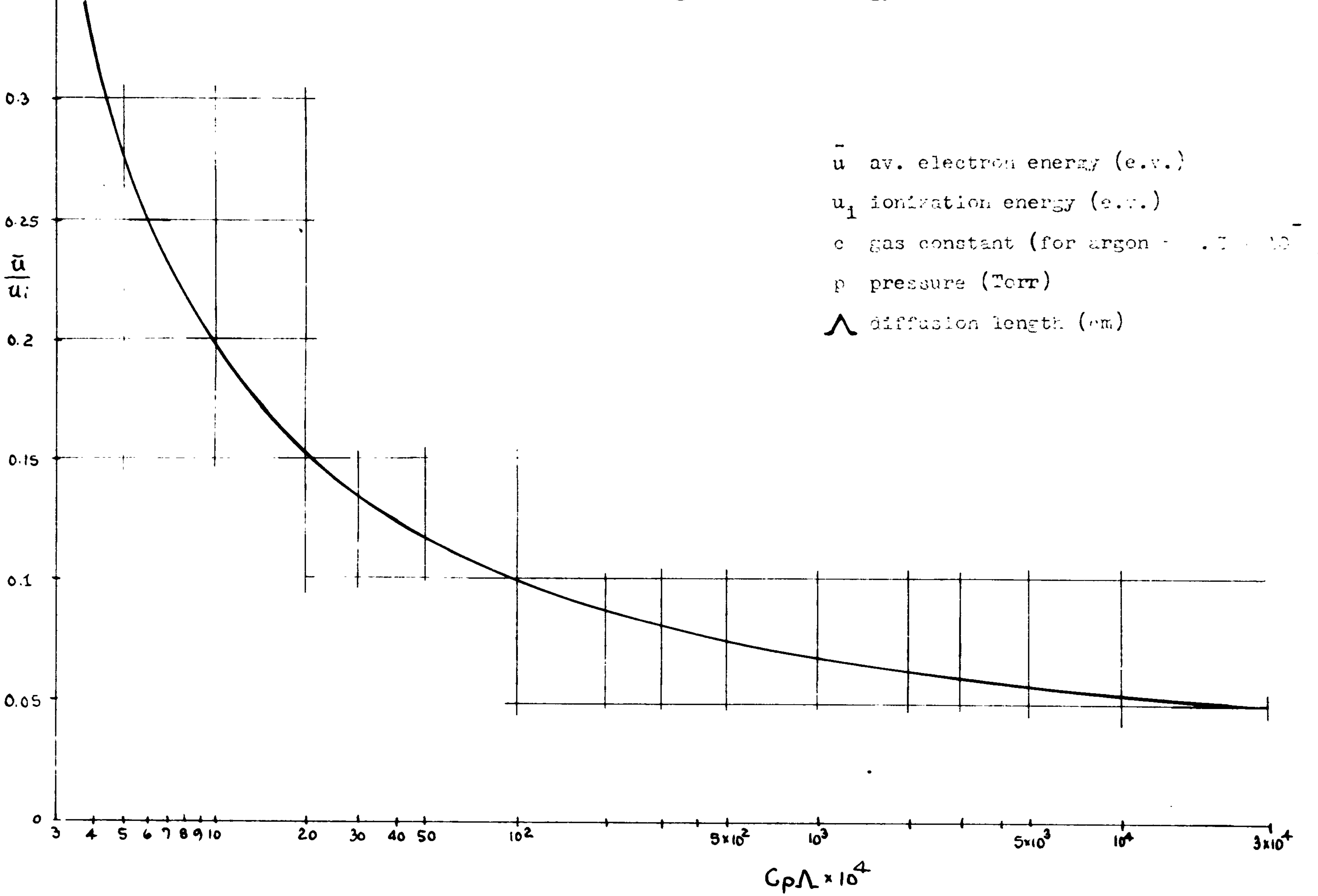
[3]Cobine, Gaseous Conductors, Dover Publications, Inc., N. Y. (1958).

Fig. 7

Average Electron Energy in Diffusion Controlled Plasma



$$\frac{1}{\Lambda^2} = \left(\frac{\pi}{L}\right)^2 + \left(\frac{2.405}{R}\right)^2 \qquad \ldots(2.4)$$

In the experiment described in this report the cylindrical tube containing the plasma is placed in a magnetic field. The magnetic field in general changes the diffusion to the radial direction due to confining effects of electron motion. This in turn modifies the ambipolar diffusion coefficient or the diffusion length. In order to calculate the average electron energy it is therefore important to evaluate quantitatively the effect of the magnetic field.

The electron flux at the wall is given by

$$\Gamma = n\bar{\mu}E - \bar{D}\left.\frac{\partial n}{\partial x}\right|_o - n\left.\frac{\partial D}{\partial x}\right|_o \qquad \ldots(2.5)$$

The electric field normal to the wall surface is caused by space charge formation, so tha first two terms can be combined using the ambipolar diffusion coefficient D_a:

$$\Gamma = -D_a\left.\frac{\partial n}{\partial x}\right|_o - n\left.\frac{\partial \bar{D}}{\partial x}\right|_o \qquad \ldots(2.6)$$

where D_a is

$$D_a = (\overset{+}{\mu}D + \bar{\mu}D)/(\overset{+}{\mu} + \bar{\mu}) \qquad \ldots(2.7)$$

The average electron theory based on the Langevin equation and on the assumption that the collision frequency is independent of particle energy, relates the diffusion coefficient D to mobility (for both ions and electrons)

$$D = 2\,\bar{\mu}\bar{u}/3 \qquad \ldots(2.8)$$

Consequently,

$$D_a = \frac{2}{3}\,\frac{\overset{+}{\bar{\mu}}\,\bar{\mu}}{\overset{+}{\bar{\mu}}+\bar{\mu}}\,(\overset{+}{u} + \overset{-}{u}) = \frac{2}{3}\,\frac{\overset{+}{\bar{\mu}}\,\bar{\mu}\,\bar{u}}{\overset{+}{\bar{\mu}} + \bar{\mu}} \qquad \ldots(2.9)$$

The right hand approximation is based on the assumption that in this case the electron energies are substantially higher than the ion energies.

The electron mobility in the direction parallel to the magnetic field is:

$$\bar{\mu}_{11} = e/m\bar{\nu} \qquad \ldots(2.10)$$

where the collision frequency $\bar{\nu}$ is

$$\bar{\nu} = p\bar{P}\,\sqrt{2\bar{u}e/m} \qquad \ldots(2.11)$$

$\bar{P}$ is the collision "probability" and p is the gas pressure in Torrs. In the direction perpendicular to the magnetic field the mobility for electrons is

$$\bar{\mu}_T = e\bar{\nu}/m\omega_b^{\,2} \qquad \ldots(2.12)$$

where the cyclotron frequency is

$$\omega_b = eB/m \qquad \ldots(2.13)$$

The effect of the magnetic field B on the much heavier ions can normally be ignored, so that the mobility of ions is in general

$$\bar{\mu} = e/M\overset{+}{\nu} \qquad \ldots(2.14)$$

where $\overset{+}{\nu}$ is

$$\overset{+}{\nu} = \sqrt{2e\overset{+}{u}/M} \quad p\overset{+}{P} \qquad \ldots(2.15)$$

In the direction parallel to the magnetic field,

$$\frac{\mu_{11}}{\overset{+}{\mu}_{11}} = \frac{M\bar{\nu}}{m\bar{\nu}} = (\overset{+}{P}/\bar{P})\sqrt{M/m} \qquad \ldots(2.16)$$

Since $\overset{+}{P}$ is of the same order of magnitude as $\bar{P}$ and $\sqrt{M/m} > 100$, one can simplify Eq. (2.9):

$$D_a(11) = \frac{2}{3}\overset{+}{\mu}\bar{u} = \frac{2}{3}\frac{e\bar{u}}{M\overset{+}{\nu}} \qquad \ldots(2.17)$$

In the direction perpendicular to the magnetic field

$$\frac{\mu_T}{\overset{+}{\mu}_T} = \frac{M}{m}\frac{\bar{\nu}\,\overset{+}{\nu}}{\omega_b^{\,2}} = \frac{1}{\gamma} \qquad \ldots(2.18)$$

Then $D_a(T)$ can be written

$$D_a(T) = \frac{2}{3}\frac{\overset{+}{\mu}\,\bar{u}}{1+\gamma} = \frac{2e\bar{u}}{3M\nu(1+\gamma)} \qquad \ldots(2.19)$$

and the ratio of the ambipolar diffusion coefficients parallel to and perpendicular to the magnetic field becomes

$$\frac{D_a\,(11)}{D_a\,(T)} = 1 + \gamma \qquad \ldots(2.20)$$

Consequently, in the presence of magnetic field the effective diffusion length is

$$\frac{1}{\Lambda^2} = \left(\frac{\pi}{L}\right)^2 + \left(\frac{2.405}{R}\right)^2 \frac{1}{1+\gamma} \qquad \ldots(2.21)$$

Substitution of typical values for γ indicates that it can differ significantly from unity for pressures below 1 Torr. Since, however, in the proposed experiment the gas pressure is above 1 Torr, one can neglect the confining effects of the magnetic field and calculate the average electron energy based on the theory in Reference 3 and the graph in Figure 3.

Based on the above-mentioned theory a long tube of 2" diameter filled to a pressure of 1 Torr of argon will have average electron energy of 1.74 e.v. Under similar conditions in xenon the electron energy will be 1.1 e.v. The effect of CO_2 is not certain because its gas constant c is not known. However, it seems likely that in view of the energy absorbing properties of CO_2 the average energy of a mixture will be increased to accomplish the same number of ionizing collisions. Xenon - CO_2 mixture appears as the most promising for ambipolar diffusion biasing since it comes to the negative slope requirements in Figure 2.

3. Microwave Cavity Design

In the second quarterly report a design of a microwave cavity in the TE_{012} mode was described. This mode allowed placement of a thermionic cathode in the central plane of the tube and gave the required transverse direction for the cyclotron field and axial direction for the d.c. field. Exploratory measurements with a tube of this type indicated that sufficient currents could be obtained in a cold cathode mode of operation and, therefore, the thermionic cathode is not essential for preliminary experimentation. Without the thermionic cathode, it was more convenient to design a cavity in a TE_{111} mode since this requires smaller diameter and can be accommodated more readily in the magnet which is available.

A microwave cavity has been designed which operates in the TE_{111} mode in a circular cylindrical cavity. The equation for this mode is

$$(fD)^2 = 47.8 + 34.8\,(D/L)^2 \qquad \ldots(3.1)$$

where

f = resonant frequency in Gc.

D = cavity diameter in inches.

L = cavity length in inches.

The cavity was designed to operate at 3 Gc. The diameter of the cavity was picked to be 2.370" to give a reasonably large ratio of L/D. This was done to produce a more uniform discharge within the plasma tube and also to decrease any end effects due to the plasma tube electrodes. The specific value of the diameter was also determined by the availability of standard brass tubing. Solving Eq. 3.1 for L results in

$$L = 8.5''$$

The microwave electric field is purely transverse to the axis of the cavity and is illustrated by solid lines in Figure 4. The microwave magnetic field has a longitudinal component and a transverse component. The transverse magnetic field is illustrated in Figure 4 by the dashed lines.

The TE_{111} mode is a doubly degenerate mode since the field pattern may be rotated 90° producing a new mode governed by the same mode equations. This degeneracy is removed when the plasma tube is inserted in the cavity.

The cavity also can resonate in the following modes at the following frequencies:

TE_{112}	3.23 Gc.
TE_{113}	3.58 Gc.
TE_{010}	3.78 Gc.

PLASMA AMPLIFIER CAVITY
AND
TUBE ASSEMBLY

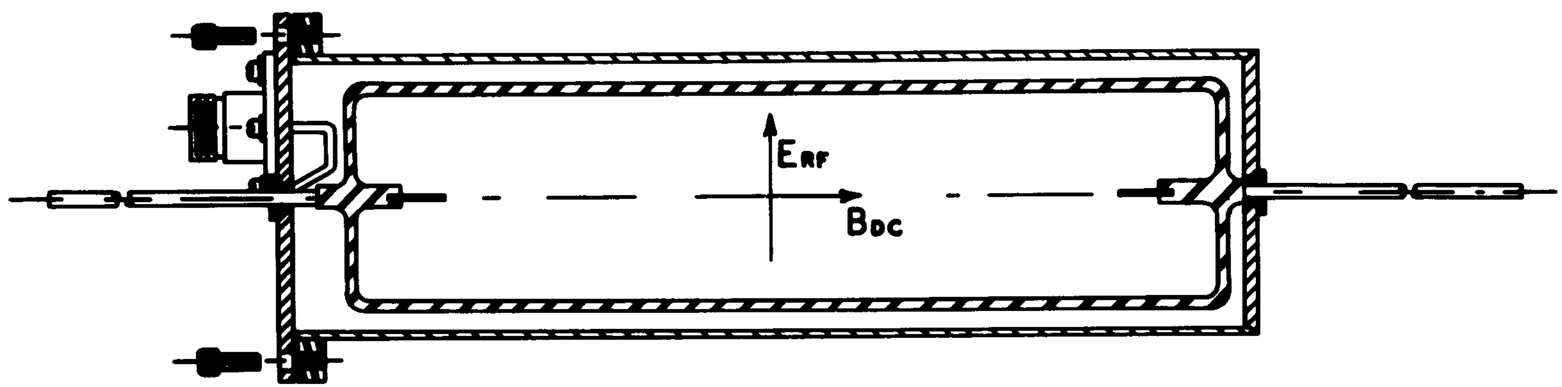


Fig. 4

The cavity is constructed of brass which is then silver plated. The cavity has a coaxial input and is coupled by means of a loop mounted on the endplate of the cavity. The coupling may be adjusted experimentally by varying the size of the loop and also by small rotations of the plasma tube with respect to the coupling loop.

The construction of the plasma tube and its incorporation into the cavity is also illustrated in Figure 4. The tube is constructed of No. 7052 glass with kovar seals and molybdenum vanes. The tube is pumped and filled through copper tubing at each end of the plasma tube. This construction allows the gas fill of the plasma tube to be varied while it is in the microwave cavity if this should become necessary.

The effect of the plasma tube upon the TE_{111} modes will be the following. First, the glass of the tube will dielectrically load the cavity, shifting the modes toward lower frequency. Second, the presence of the plasma tube vane electrodes will separate the two degenerate modes. The mode which has its electric field orthogonal to the vanes will be appreciably further shifted in frequency. The mode with its electric field parallel to the surface of the vanes will be cutoff beyond the vanes, effectively shortening the length of the cavity and raising the frequency.

The lower frequency mode also will have a lower Q_o since the plasma tube electrodes are not a low loss material.

Either mode may be easily coupled to and used for purposes of the experiment. The higher frequency mode would be preferred because of its high Q_o.

Figure 5 is a photograph of the cavity and plasma tube.

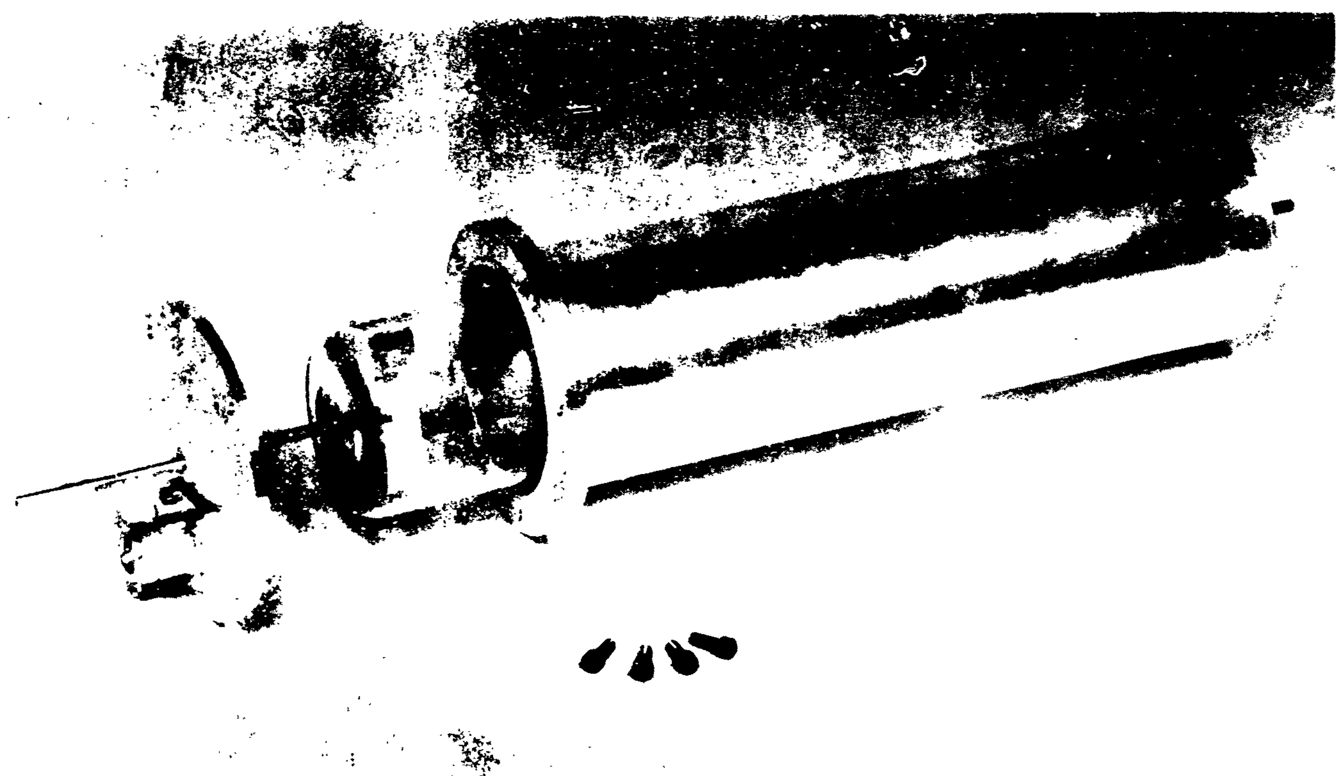


Fig. 5

4. Instrumentation

4.1 Microwave Instrumentation

Figure 6 shows the experimental arrangement which will be used to observe gain in the plasma tube. The equipment is arranged to display on an oscilloscope the reflection coefficient of the microwave cavity which contains the plasma discharge.

The klystron is swept in frequency across its entire mode of oscillation. Figure 7 shows the patterns which should be observed on the oscilloscope at cyclotron resonance for various conditions of the plasma within the cavity. Figure 7a shows the mode pattern with no plasma and the cavity approximately matched. Figure 7b shows the mode pattern with a lossy plasma at cyclotron resonance. The cavity will become mismatched and the Q will become appreciably lower. Figure 7c shows the mode pattern for a plasma showing gain. In this case the mode pattern will show a hump instead of a dip since more power is reflected from the cavity than is incident upon it. Figure 7d shows the mode pattern when the plasma breaks into oscillation.

One precaution which will be observed in making these measurements is in keeping the klystron power sufficiently low. Since only milliwatts may be expected from this plasma experiment, the klystron power must be kept to the one milliwatt

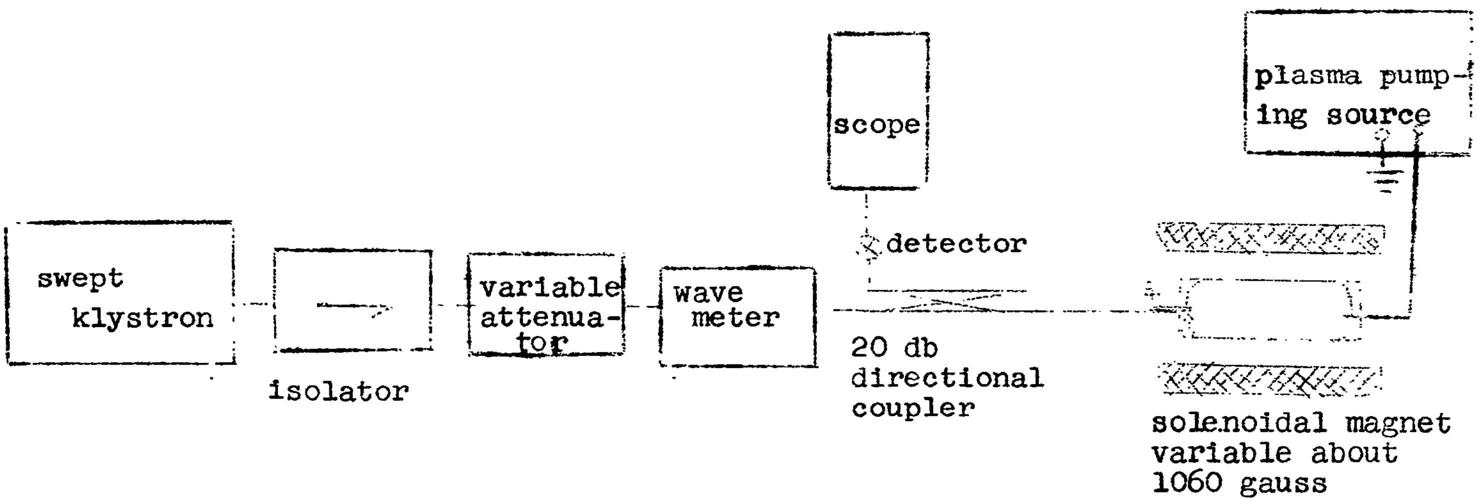
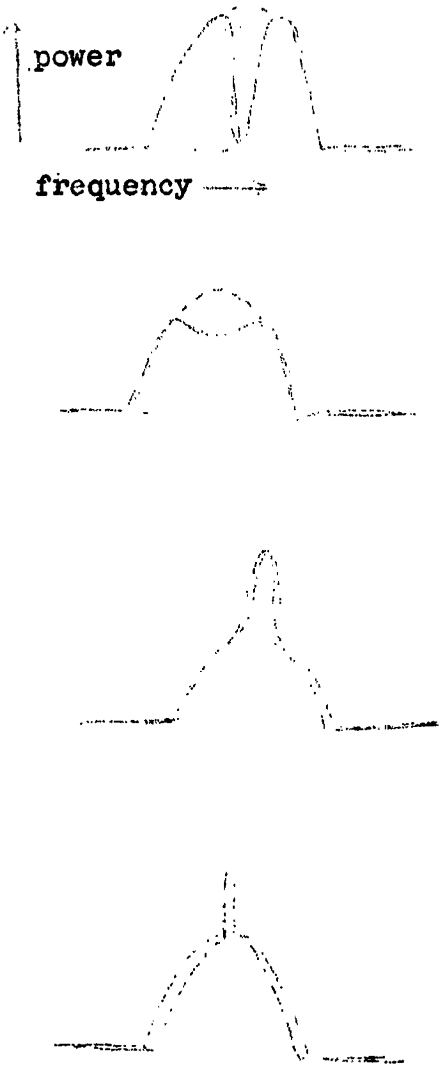


Figure 6

Microwave Measurement Equipment



a) Mode pattern without plasma

b) Mode pattern with lossy plasma

c) Mode pattern with plasma showing gain

d) Mode pattern with oscillations

Figure 7

level or below. This however presents no experimental difficulty in detection.

Another precaution which must be taken is to examine the effects of plasma loading on the other modes of the cavity whose resonant frequencies are near that of the TE_{111} mode. The loaded Q of any mode whose frequency ω is sufficiently near to that of the TE_{111} mode so that $|\omega - \omega_{111}| \lesssim \nu$ may be substantially lowered by the plasma in the vicinity of electron cyclotron resonance. Hence its resonance broadening may be such that a probing microwave signal may to some extent simultaneously interact with this mode as well as with the TE_{111} mode. Furthermore, the strong reactance of the plasma near cyclotron resonance and near the TE_{111} mode, but differing from either of them by a little more than the collision frequency ν, may produce a large resonance frequency shift in nearby modes. Under certain conditions this frequency shift could be opposite in sign to the frequency shift produced by the plasma. The result would be that the cavity mode separations with the plasma present may be substantially less than the mode separations of the empty cavity. In order to insure that this is not the case, careful measurements must be made to explore the cavity response to each mode which can exist both with and without the plasma present in the vicinity of several hundred megacycles of the TE_{111} mode.

Qualitatively, at least, some of these modes may interact essentially in the same manner as the TE_{111} mode and be amplified, whereas other modes may contribute attenuation. If it is found that the presence of nearby modes causes difficulty in the manner mentioned above, it may be necessary to incorporate means for suppressing the undesired modes, such as slots in the cavity walls.

4.2 <u>Vacuum System</u>

The vacuum system with provisions for gas filling consists of three separate basic units integrally connected and housed as a single unit.

(a) Standard high vacuum system with bake-out oven.

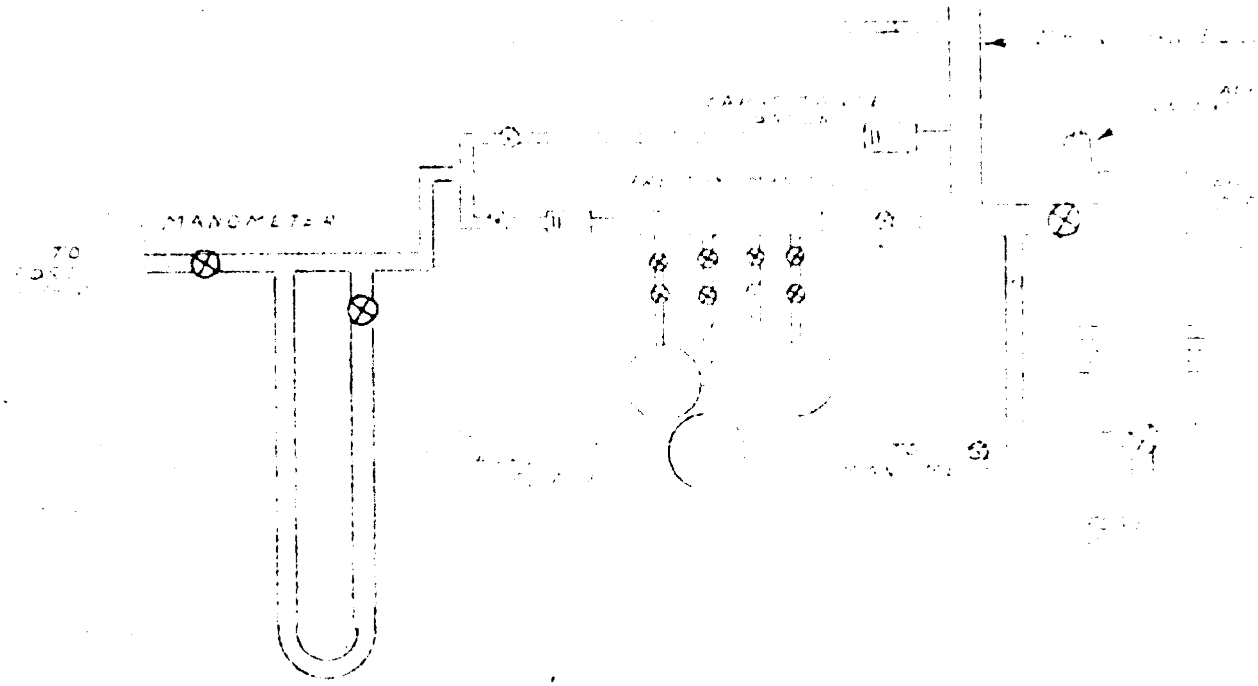
(b) Gas mixture reservoir with connections and valves for spectroscopically pure gas bottles.

(c) Gas pressure measuring system.

These three basic units are composed of the following components:

(a) High Vacuum System

1. Fore pump
2. Air cooled metal Veeco diffusion pump and cold trap
3. Main all metal manifold with glass section for tube attachment
4. Main high vacuum shut off valve between cold trap outlet and manifold


MANOMETER
TO

5. Baird Alpert ionization gauge between main vacuum valve and diffusion pump cold trap
6. Manifold to fore-pump bypass line with high vacuum valve
7. Shutoff valve between lower end of diffusion pump and fore pump
8. Bake-out oven and temperature control to 500°C
9. Ionization gauge amplifier

(b) Gas Mixture Reservoir Section

1. 1 1/2" diameter stainless manifold reservoir with high vacuum valved connection to main manifold
2. Four ports from reservoir manifold for gas bottle connections, each port having two high vacuum valves between reservoir manifold and gas bottles.

(c) Gas Pressure Measuring System

1. Capacitance gauge tube for main manifold pressure
2. Capacitance gauge tube for reservoir manifold pressure
3. Manometer (dibutyl phthylate) for capacitance reference pressure

4. Vacuum line from capacitance gauges through manometer to fore pump for evacuation of pressure measuring section

5. Capacitance measuring instrument

The tube processing prior to gas filling is done according to a standard procedure. The tube is connected to high vacuum manifold and pumped down. The tube is baked at approximately 500°C for several hours and until outgassing is complete. Liquid nitrogen is admitted to the cold trap and the tube is cooled to near room temperature before the oven is removed. The tube is now ready for gas filling. Manifold pressure should be down to 5×10^{-7} mmHg or lower.

The gas mixture reservoir which is connected to the main manifold through a valved line is at the same pressure as the main manifold since it was also pumped with the tube.

Closing the valve between the reservoir and the manifold will now isolate this section from the tube manifold.

This section is now filled with the desired mixture of gases to a total pressure in excess of that desired in the tube. Measurement of the gas total and partial pressures will be explained under measurement procedure.

The premixed gas can now be admitted to the tube and the main manifold by closing the main vacuum valve which isolates the manifold from the pumping system and the cold trap. Opening of the valve between the main manifold and the gas mixture reservoir admits the premixed gas to the tube and manifold.

The capacitance gauge tubes are glass cylinders sealed at each end to kovar end caps. One end cap has an internal post with a plate attached, the other end has a vacuum-tight bellows also with a plate attached. Spacing between the plates is approximately .060" with equal pressure on each side. When pressure is applied to the bellows side of the gauge, the gap between the plates is reduced and the capacitance changes. A capacitance measuring instrument connected across the tube will measure this change. The change in capacitance is used to measure the gas as admitted to the tube in one case and the gases as admitted to the mixture manifold in the other.

The volume on the fixed plate side of the gauge is always connected to the evacuated manifolds. The bellows or movable side is always connected to a manometer or other measuring device and to a vacuum source. In addition, a valve or stop cock is used to admit air into this section and the manometer reads this pressure.

An initial pressure is admitted to the measuring system to close the gap to a region of high sensitivity or large capacitance change for a small change in pressure for most accurate measurement.

The capacitance bridge connected across the gauge tubes is now balanced and the pressure is now changed by the amount of gas desired to be admitted into the system. This pressure is read on the manometer. The use of dibutyl phthylate permits a factor of 12.5 expansion in column height as compared with mercury height and is therefore much easier to read for gas pressures in the 1 Torr range.

As gas is admitted from the gas bottles through the double valves the capacitance bridge reading returns toward the established reference. When the capacitance bridge reads the reference value, the gas admitted into the system is the same as the pressure read by the manometer since the pressures on each side of the capacitance gauge tube have been balanced to the reference capacitance.

5. Measurements

5.1 D. C. Discharge Measurement

The first measurements were performed in a tube of 4 cm. in diameter consisting of a circular cathode and an anode spaced 6 cm. apart. The tube was filled with a mixture for argon and CO_2 at a total pressure of about 2 Torrs and a partial pressure of CO_2 of approximately 2 percent. The tube was connected to a d.c. supply through a resistance of 4 K ohms. The breakdown occurred first when the voltage across the tube was 500 volts. After breakdown the voltage dropped to 450 volts. One could observe a dark cathode fall region extending about 4 mm. from the cathode surface and a luminous sheath completely covering the cathode surface. As the voltage across the tube is increased, the luminous region adjacent to the cathode expands toward the anode. At about twice the breakdown voltage the luminous plasma extends all the way to the anode. The introduction of a magnetic field up to about 1 kilogauss does not affect the operation of the discharge, its appearance or its voltage current characteristics.

At the breakdown point the current is about 5 milliamperes. On increasing the voltage to a thousand volts the current increases to about 400 milliamperes in a more or less linear fashion. Oscilloscopic observations of the voltage across the tube did not reveal any significant random noise or low frequency ion oscillations.

During operation the cathode heats up due to ion bombardment and also sputtering can be observed on the glass envelope adjacent to the cathode.

On reducing the voltage after a breakdown one can still maintain the discharge, but the current drops rapidly. In view of low current this mode of operation has not been investigated further.

The current density in the plasma is adequate for the desired operation. Also the fact that the plasma runs in a quiet mode of operation with no instabilities often observed in a plasma is encouraging. On the other hand, the nonuniform appearance of the plasma glow which tends to fill only part of the tube indicates that the diffusion losses in this particular geometry and pressure range were such that the plasma could not be treated as an essentially uniform positive column. The sputtering problem is not necessarily serious if the cathode is placed outside of the microwave structure. However, a metallic deposit in a microwave structure may have a detuning effect on the cavity mode and also may introduce additional losses to the cavity Q.

Conceivably, the plasma uniformity can be improved by operation at lower pressure. On the other hand, cathode sputtering and its affect on cavity performance is a rather serious problem for the cavity under test. It was therefore decided for preliminary experimental purposes to excite the plasma by r.f. oscillations by an r.f. generator connected to the external electrodes. A substantial improvement in uniformity of the plasma and reduction of an electrode sputtering was realized at this time.

5.2 Microwave Measurements

Cold tests have been run on the cavity with and without plasma tube. The TE_{111} mode was observed by noting a dip in the klystron mode pattern. In the empty cavity it occurs at 3.00 Gc. The fact that this was the TE_{111} mode was confirmed by perturbing the cavity with a metallic needle mounted on a dielectric rod. The shift in the cavity frequency as the needle is moved across the length of the cavity corresponds to a single half wavelength variation.

With the plasma tube in the cavity the TE_{111} modes were split apart in frequency and were observed at 2.860 Gc. and 3.040 Gc. The higher frequency mode had the higher Q as would be expected.

No measurements have yet been made with the discharge fired in the cavity. These measurements are planned for the next quarter.

When a d.c. discharge is run in the plasma tube, sputtering occurs around the cathode area. This sputtering leaves a thin film of highly resistive material on the inner plasma tube wall. Cold cavity measurements were made on a plasma tube which had been operated with a d.c. discharge for about 10 minutes. The effect of the sputtering was to damp out the desired mode. For this reason it was decided to utilize an r.f. discharge.

The r.f. source operating at 27 Mc was connected through a proper coupling network to the two metal electrodes. The plasma could be easily ionized over a wide range of r.f. power. The plasma was quite uniform in appearance and no significant sputtering was observed.

5.3 Probe Measurements

An attempt was made to check the average electron energy calculation by probe measurements. In the d.c. case the results were inconclusive because of nonuniformity of the plasma in the vicinity of the probe. In the r.f. case there is some uncertainty at present about the effects of r.f. interference. Modification of the technique to reduce r.f. interference is under consideration.

6. Work in Progress and Plans for the Next Quarter

6.1 Theory

The study of magnitude and direction of d.c. "pumping" resulting from ambipolar diffusion gradients will be studied for the case of d.c. plasma excitation and r.f. plasma excitation. The effect of plasma on the configuration of microwave modes in cavities and waveguides also will be studied further. The thorough understanding of both problems is needed to assess and optimize the various modes of interaction between the d.c. field and r.f. field in an amplifying plasma.

In preparation for the final report a general assessment and comparison of various techniques explored during the contract for fast wave plasma amplification will be carried out.

6.2 Experimental

The experimental studies directed at the observation of oscillations in microwave cavities are continuing. In addition, the amplifying structures consisting of plasma-filled waveguide will be designed and tested.

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